Vorticity and Turbulent Properties in Tidal and Shelf Bottom Boundary Layers

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LONG-TERM GOALS

Our goal is to contribute to a better understanding of small-scale processes in shallow water and coastal flows, in order to provide better, more physically-based parameterizations for coastal models. We seek to understand how high Reynolds' number coastal flows interact with boundaries producing tangential stress, dissipation, mixing, and secondary circulation. Detailed comparison of our field observations with direct numerical simulations will hopefully improve contemporary model parameterization schemes.

OBJECTIVES

The objective is to observe mean and turbulent flow quantities in an energetic tidal channel over a relatively smooth channel bottom and over topography under various stratification conditions. These observations throughout the water column are being contrasted with published results from current meters on tripods, from wind tunnel experiments, and theory. Particular emphasis is placed on the observation and interpretation of small-scale vorticity in conjunction with other mean and turbulent flow quantities. Similarity scaling laws of mean and turbulence properties in the oceanic turbulent boundary layer are examined. These results will be very useful toward parameterization of turbulence in numerical models.

APPROACH

Our approach is to measure vorticity, velocity, dissipation and water properties within bottom boundary layers in tidal channels with variable bottom topography. The most notable sensor is an electromagnetic vorticity detector, which determines a component of relative vorticity based on the principles of motional induction. An experimental site in Pickering Passage in the South Puget Sound, WA, has been selected based on a detailed multi-beam bathymetry survey. Topographic relief is less than 0.3 m for distances of 200 m upstream of the measurement site. Other locations exhibit regular patterns of bedforms, such as waves with heights of 0.5-1 m and wavelengths of 20-30 m, and a prominent ridge about 500-m long, rising 10 m above a flat bottom. In addition to velocity and vorticity, observations of temperature, electrical conductivity, pressure, altitude above the bottom, and turbulent kinetic energy dissipation rate are obtained. Vehicle attitude (i.e., pitch, roll, yaw, pitch-rate and roll-rate) is measured to correct vorticity and velocity measurements for vehicle motion and to rotate observations into true horizontal and vertical components. The instrument can be slowly winched vertically while the vessel is anchored or slowly moving.

WORK COMPLETED

We have conducted several experiments measuring vorticity and other turbulent properties in Pickering Passage, Washington. Several technical reports have been published. One paper describing the details of instrument is in press (Sanford et al., 1999). Another paper discussing turbulence properties in an unstratified turbulent boundary layer has been published (Sanford and Lien, 1999). We have also examined details of turbulent vorticity flux spectra in a paper submitted to the Journal of Geophysical Research (Lien and Sanford, 1999).

RESULTS

We have had a rewarding and productive biennium. Our work has resulted in fundamental discoveries, refereed publications and numerous talks, including one at ONR Headquarters. The source of our success is the unique data set from Pickering Passage, WA. So far we have emphasized studies of only one of the four sets of observations, namely the one under homogeneous density conditions. Our efforts at analysis and interpretation have resulted in three publications. Our new findings from these analyses include:

- the demonstration of the importance of a multi-beam topographic survey around the site of a BBL experiment,
- the presence of multiple log layers in the bottom boundary layer (BBL),
- verification in large Reynolds-number flow that $\nu \langle \zeta'^2 \rangle = \varepsilon$, where ν is the molecular viscosity and $\langle \zeta'^2 \rangle$ is the enstrophy,
- the agreement of velocity spectra and momentum flux co-spectra with empirical forms found in the well-known Kansas experiment (Fig. 1),
- a new method of estimating the friction velocity based on the vorticity flux and a similarity scaling of vorticity flux in an unstratified BBL (Fig. 2), and
- the construction of a model vorticity flux co-spectrum based on our unique vorticity observations (Fig. 3).

The proposed similarity scaling of turbulent vorticity flux is consistent with a down-gradient concept of flux and an eddy diffusivity scaling commonly used in an unstratified boundary layer, i.e., $<w'\zeta_y'> = \nu_\zeta \partial_z <\zeta> = u_*^2/Z$, where Z is the height above the bottom, ν_ζ the eddy diffusivity of vorticity, and u_* the friction velocity. The model spectrum of vorticity flux co-spectrum is constructed based on (1) the spectral slope of *–7/3* in the inertial subrange predicted by the dimensional analysis, (2) the similarity scaling of the vorticity flux, and (3) the observed scale of dominant vorticity flux. Our study of vorticity flux is unique and useful because the vorticity flux can be used to estimate the friction velocity and is directly related to the divergence of the momentum flux, the force that turbulence exerts on the mean flow. Our results may offer useful guidance for numerical modelers to improve their parameterization skill.

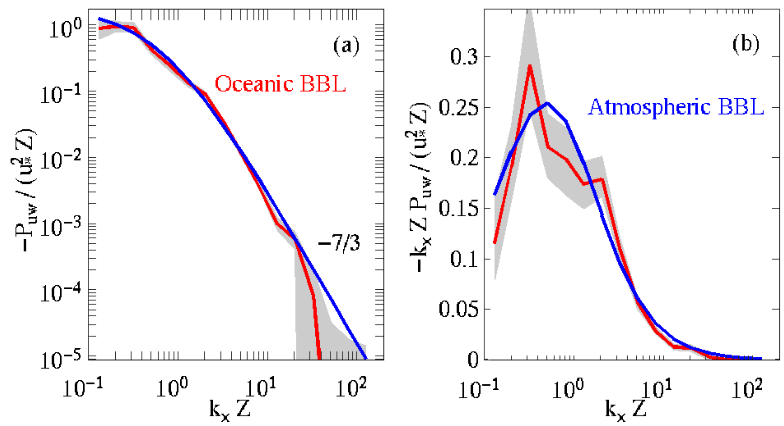

Figure 1: Comparison of observed normalized vertical flux of horizontal momentum co-spectrum P_{uw} (red curve) with the universal momentum flux co-spectrum (blue curve) found in the neutral atmospheric boundary layer. The k_x is the streamwise wavenumber, Z the height above the bottom, and u_* is the friction velocity. In the turbulence inertial subrange, the momentum flux co-spectrum has a -7/3 spectral slope.

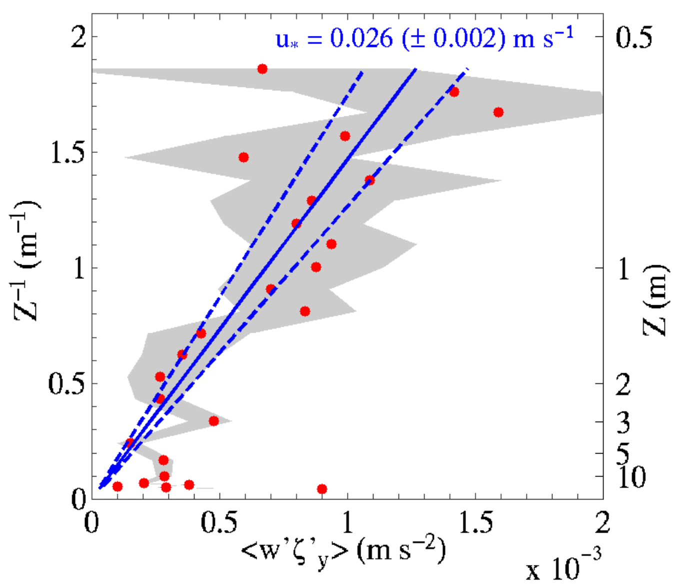

Figure 2: Vertical flux of spanwise vorticity averaged in depth bins as a function of Z^{-1}. For reference the actual depth scale is on the right margin of the figure. The red dots are the observed mean vorticity flux and the shading denotes the 95% confidence interval. The blue solid line is the

fitted vorticity flux as a function of Z^{-1}. The estimated u_* is 0.026 m s^{-1} with the 95% confidence interval of 0.002 m s^{-1} denoted by the two dashed blue lines. This estimate of u_* agrees with the value calculated by conventional methods (Sanford and Lien, 1999).

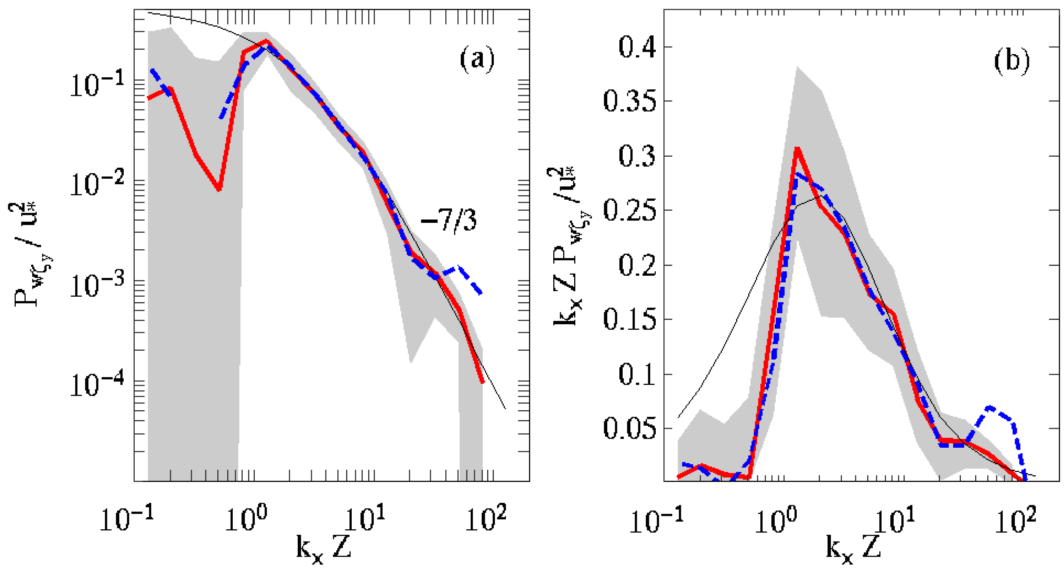

Figure 3: Comparison of observed vertical flux of spanwise vorticity co-spectrum with our model spectrum. The red curve is the observed vorticity flux co-spectrum and the blue dashed curve is the observed spectrum corrected for the sensor response function. The thin black curve is our model vorticity flux co-spectrum. The panel (b) is the variance-preserving plot of the panel (a). A -7/3 spectral slope at large normalized wavenumber is shown to agree with the model spectrum in the inertial subrange.

IMPACT/APPLICATION

Our instrument provides the first field measurements of turbulent vorticity and vorticity flux in a natural turbulent boundary layer. Vorticity is the most fundamental variable of turbulence. Therefore, our measurements provide new ways to study turbulence. There are many potential applications of our measurements in the ocean. In particular, our instrument is suitable for measuring the vortex force, which is a major driving mechanism of Langmuir circulation and sediment suspension. The instrument can be used to measure potential vorticity with additional density sensors. Since internal waves do not carry potential vorticity, this is the key quantity to distinguish internal waves and turbulence in a stratified flow.

Further study of form drag in the turbulent boundary layer is needed. We demonstrate that the profile method may yield a non-local stress estimate, which depends crucially on the upstream condition of bottom topography. To study the turbulent boundary layer, it is important to know the surrounding bathymetry. Previous researches have often shown that the profile method yields an excess stress. Form drag has been suggested for the excess stress. We need direct evidence for the suggested form drag.

Similarity scaling and spectral properties of stratified turbulence should be investigated. Similar studies have been attempted in the atmospheric boundary layer where the stratification is often strongly evolving without an extensive period of stable condition. Both internal waves and turbulence coexist in the stable stratified flow. The existence of internal waves hinders the similarity scaling of turbulence because there is no apparent scheme to separate internal waves and turbulence in the stratified flow. Our next task will be devoted to the similarity scaling of turbulence in a stratified oceanic bottom boundary layer.

TRANSITIONS

There are several potential transitions to Naval applied projects in the field of wake studies and EM signals in the ocean.

RELATED PROJECTS

It is certain that the sensor is appropriate for participation with many science projects now underway in shallow-water bottom boundary layers, such as ONR's CMO project, to study mixing, internal waves, and bottom stress.

REFERENCES

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PUBLICATIONS

Lien, R.-C., and T. B. Sanford (1999), Velocity and vorticity flux spectral characteristics in an unstratified turbulent boundary layer, submitted to *J. Geophys. Res.*

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